Astrometry and Subpixel Detector Characterization

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WPS March 3, 2016

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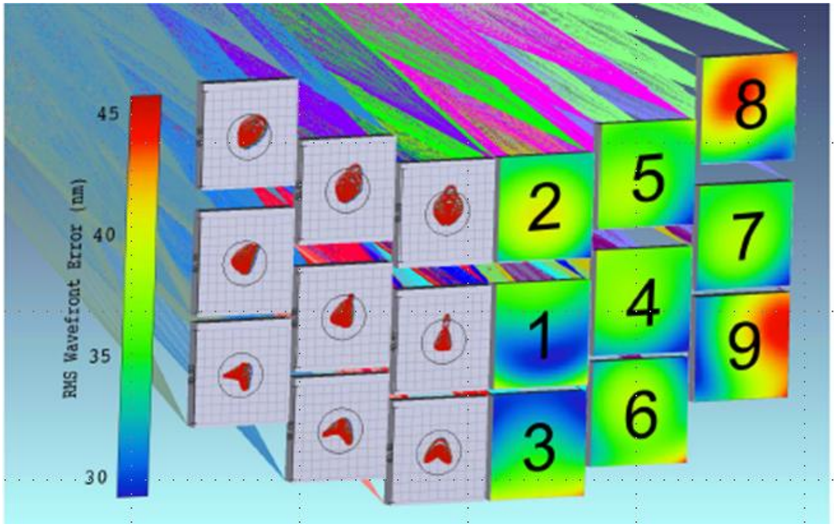
Outline

- Why is subpixel characterization important?
  - Accurate photometry and astrometry
  - Focal plane not Nyquist sampled
- How does subpixel characterization work?
  - Projection of a fringe “ruler” onto the detector
  - Fit the fringe and determine systematic pixel position errors
- Prior work with CCDs
- Status of experiments with H2RG IR detector

WFIRST Focal Plane

- Detector not Nyquist sampled
  - Pixel size 0.1 arcsec
  - λ/D @1.2um ~0.1 arcsec
  - ~1 pixel/(λ /D) but Nyquist sampling is 2 pixels/(λ /D)
- Nyquist sampling:
  - Gives accurate astrometry and shape measurement
  - Can be obtained by dithering the image on the detector.

    Significant errors can occur if the QE within a pixel is not constant. In CCDs errors at the 0.01pix level are common. Using the sqrt(N) argument works but N can be large (~10^6) and the noise needs to be uncorrelated.



PSF (even with perfect optics), varies across the FOV.

QE varies within a pixel and is not fully repeatable between pixels. When dithering an image ½ pixel, QE changes across a pixel result in significant photometric errors -> astrometry/shape errors

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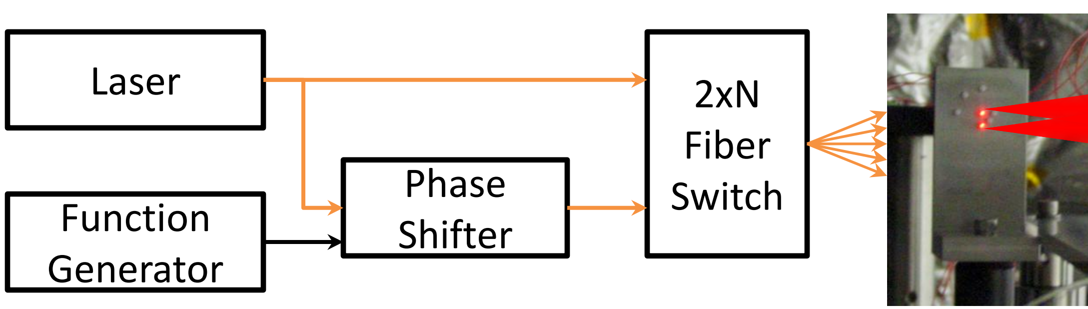
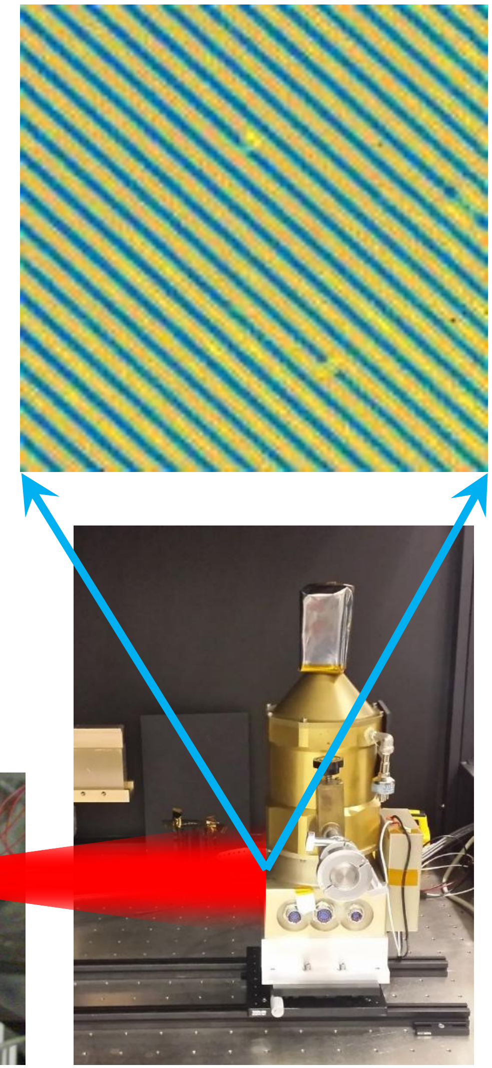
Experiment Setup with H2RG Detector

- Laser beam split to two fibers
- Relative phase of two paths is modulated
- Multiple pairs of fibers can project fringes with different orientations and spatial frequencies
- Fringe serves as a stable, spatially precise reference



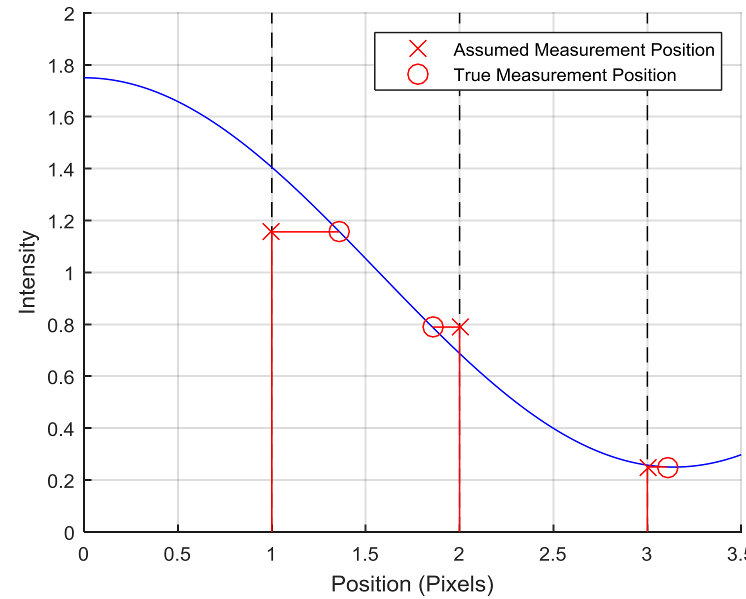


1D Example of Fringe "Ruler"

- The sine wave is assumed to be sampled at integer pixel locations.
- If pixel is actually dislocated, the measurement will be attributed to the wrong spatial location.
- The fringe provides a precise ruler to place the measured value at its true location.

Note: Fringe must be moved to multiple locations because offsets near the peak and trough can't be resolved.

Fringe spacing >> pixel width measure pixel position. < pixel width measures fourier components of the Fourier transform of the intrapixel QE(x,y)



The near perfect sinusoidal fringes are a result of interference between two wavefronts from single mode optical fibers, whose spherical wavefront can approach $\lambda/10{,}000$.
The purity of this sine wave provides unequalled geometric and photometric accuracy.

Detector Linearity

- Nonlinearity observed by performing multiple non-destructive reads of a single pixel
- Nonlinearity model:
  - Observed # photoelectrons, Q [e-]
  - True # photoelectrons, q [e-]
  - Nonlinearity coefficient, $\beta = 3.6\text{e-}7$ [1/e-]
  - $Q = q - \beta q^2$
- Nonlinearity calibration:
  - Observed Pixel Value, $\tilde{I}$ [ADU]
  - Detector gain, $G = 2.35$ [e-/ADU]
  - Calibrated Pixel Value, $I = \frac{1-\sqrt{1-4\beta\tilde{I}G}}{2\beta G}$

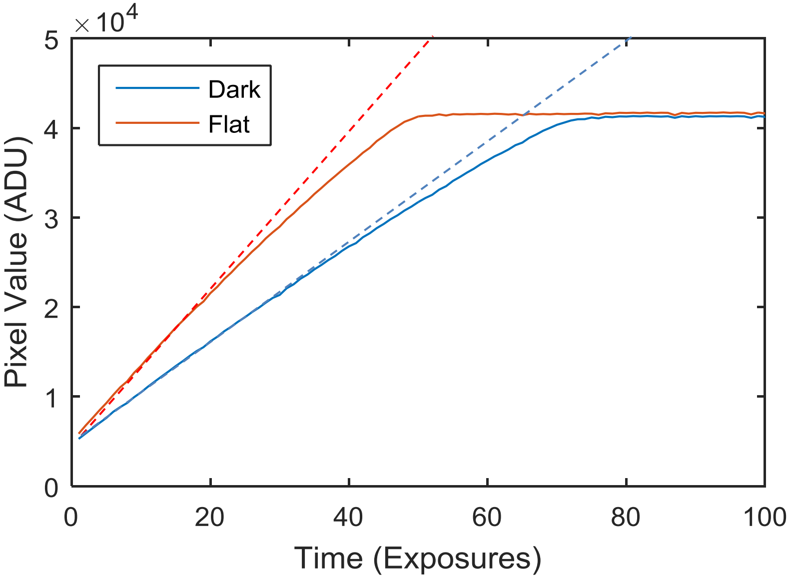
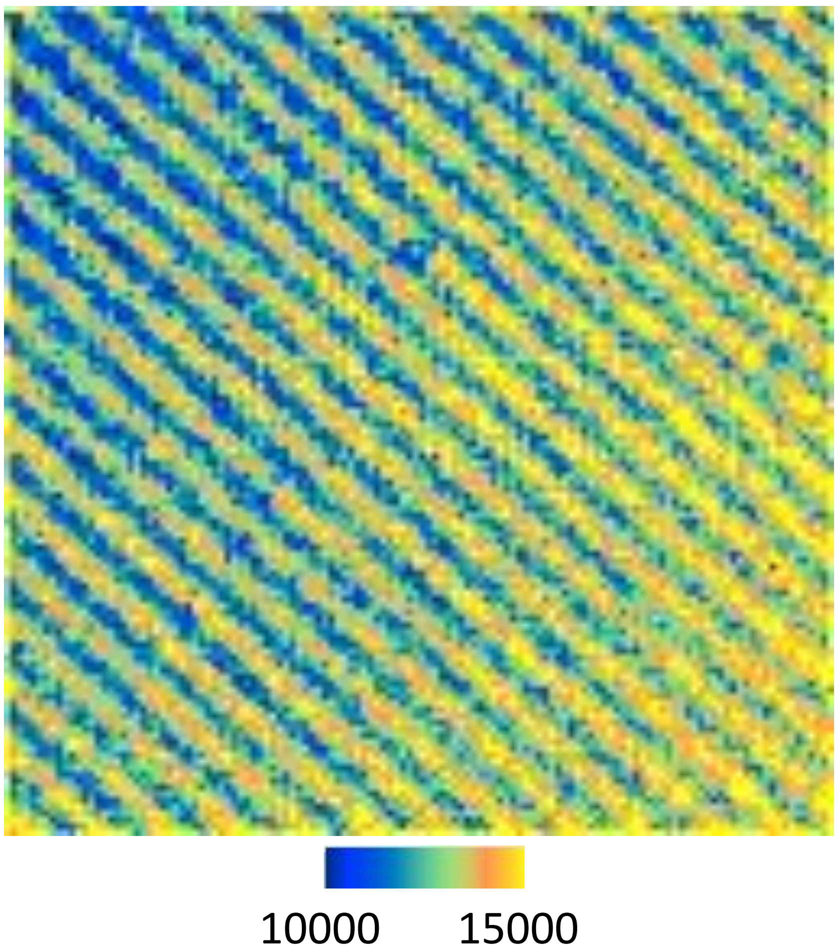


Image Normalization

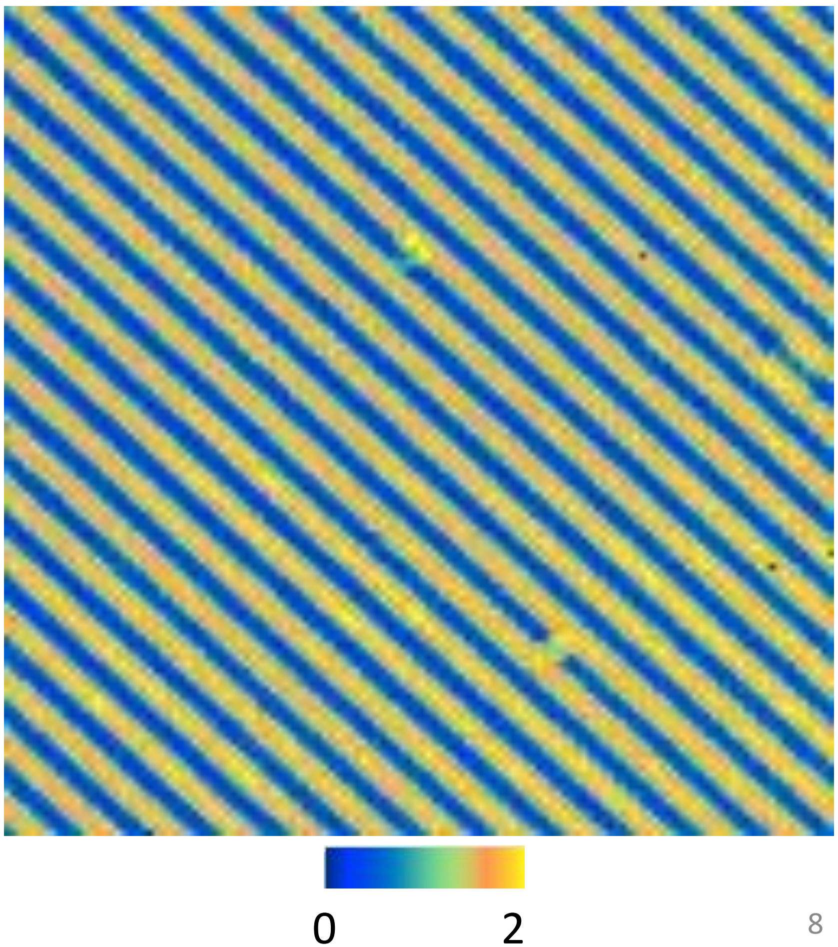
- Mixing of the two fields gives the observed intensity
  $I = I_1 + I_2 + 2\sqrt{I_1 I_2}\sin\varphi$
- I_1 and I_2 are estimated by collecting "flat" $F^{i,j}$ images
- Reset noise and dark current estimated by collecting "dark" $D^{i,j}$ images
- Multiple flat and dark images are averaged to eliminate read noise
- Normalization: $\hat{I}^{i,j} = \frac{I^{i,j} - \langle D^{i,j} \rangle}{\langle F_1^{i,j} \rangle + \langle F_2^{i,j} \rangle - 2\langle D^{i,j} \rangle}$
- Normalized pixel is ideally: $\hat{I} = 1 + \frac{2\sqrt{I_1 I_2}}{I_1 + I_2}\sin\varphi$

Image Normalization (cont.)

Raw Image



Normalized Image



Solving for Pixel Displacement

Collect many images of a fringe in a single orientation while varying the phase of the fringe

1. **Spatial Fit** - Independently fit every image of the fringe to estimate the intensity, visibility, phase, and orientation of the fringe.
   - <u>Result is estimated value of the true fringe at every pixel.</u>
   - Large number of pixels averages out pixel position errors.
2. **Temporal Fit** – For one pixel at a time, independently fit all images to the spatial fit to estimate the temporally consistent intensity error and position error.
   - <u>Results are the estimated pixel offsets along the fringe</u>
   - Large number of images averages out read noise and photon noise errors.
3. **Iterate** using corrected pixel locations

Repeat for several fringe orientations

Fringe Spatial Fit

- A least-squares fit is performed to each normalized image to estimate the 5 parameters of the true fringe in each image
- Ideal fringe: $\hat{I} = 1 + \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} \sin\varphi$
- Parameterized fit: $\hat{I}_n^{i,j} = I_n + V_n \sin\left(\varphi_n + \vec{k}_n \cdot \hat{r}^{i,j}\right)$
- Parameters: $\{I_n, V_n, \varphi_n, k_{n,x}, k_{n,y}\}$

Pixel Temporal Fit

- Phase term of every image differs because of modulation
- Expected pixel value from spatial fit is

$$\hat{I}_n^{i,j} = I_n + V_n \sin\left(\varphi_n + \vec{k}_n \cdot \hat{r}^{i,j}\right)$$

- Add two new parameters for temporal fit. Allow for variation in mean, amplitude, and position along fringe at each pixel.

$$\begin{aligned}\hat{I}_n^{i,j} &= I_n \iota^{i,j} + V_n \alpha^{i,j} \sin\left(\varphi_n + \langle \vec{k}_n \rangle \cdot \vec{r}^{i,j} + \delta r^{i,j}\right) \\ &= I_n \iota^{i,j} + V_n \sin\varphi_n \underbrace{\left(\alpha^{i,j} \cos\left(\langle \vec{k} \rangle \cdot \vec{r}^{i,j} + \delta r^{i,j}\right)\right)}_{C^{i,j}} + V_n \cos\varphi_n \underbrace{\left(\alpha^{i,j} \sin\left(\langle \vec{k} \rangle \cdot \vec{r}^{i,j} + \delta r^{i,j}\right)\right)}_{S^{i,j}}\end{aligned}$$

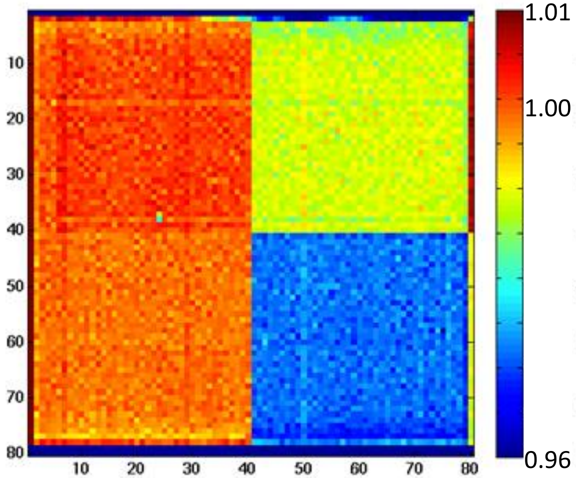
- Temporal parameters solved via pseudoinverse

$$\begin{bmatrix} \iota^{i,j} \\ C^{i,j} \\ S^{i,j} \end{bmatrix} = \begin{bmatrix} I_1 & V_1 \sin\varphi_1 & V_1 \cos\varphi_1 \\ I_2 & V_2 \sin\varphi_2 & V_2 \cos\varphi_2 \\ \vdots & \vdots & \vdots \\ I_N & V_N \sin\varphi_N & V_N \cos\varphi_N \end{bmatrix}^{\dagger} \begin{bmatrix} I_1^{i,j} \\ I_2^{i,j} \\ \vdots \\ I_N^{i,j} \end{bmatrix}$$

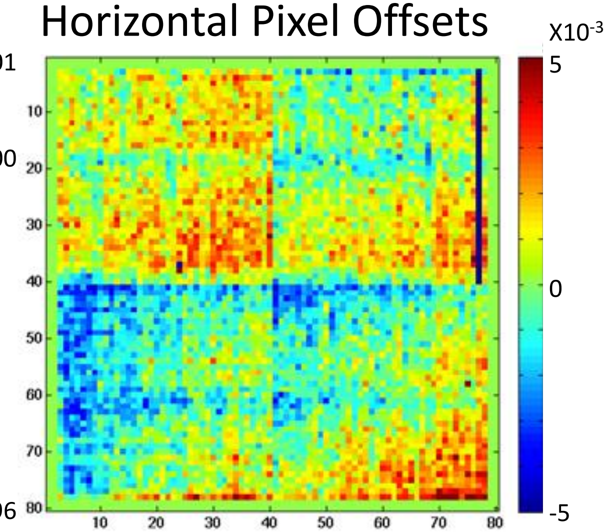
- Pixel offset along $\vec{k}$: $\delta r^{i,j} = \dfrac{1}{\left|\langle \vec{k} \rangle\right|} \left(\arctan \dfrac{S^{i,j}}{C^{i,j}} + m2\pi - \langle \vec{k} \rangle \cdot \vec{r}^{i,j}\right)$

Example Results from CCD

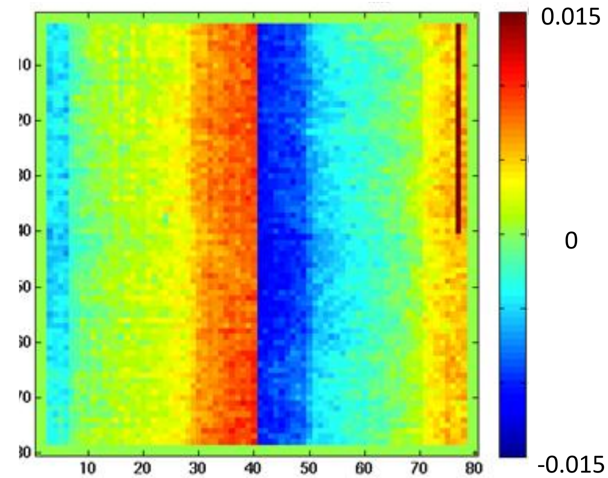
Flat Field Response



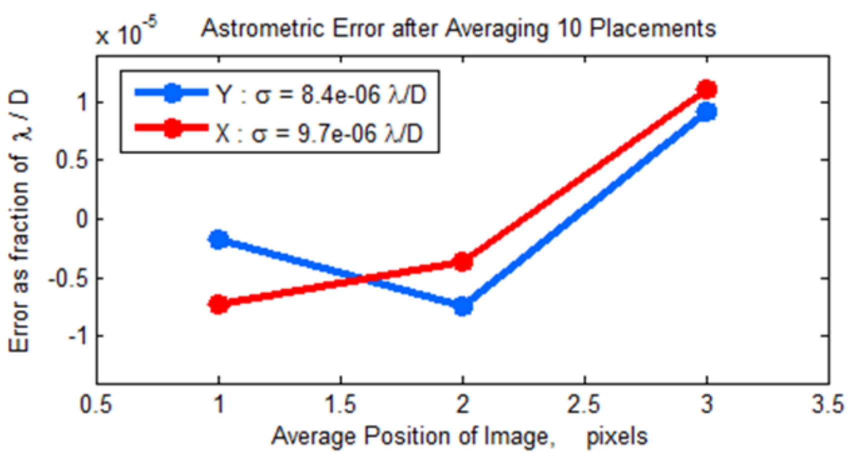
Horizontal Pixel Offsets

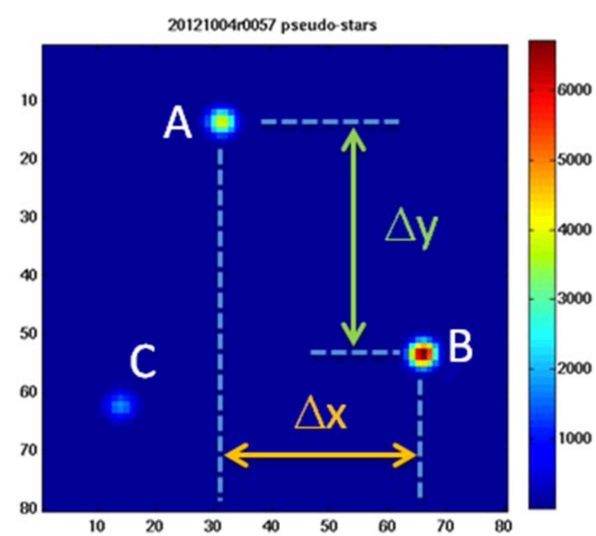


Vertical Pixel Offsets



- Detector has four quadrants each with a different flat field response.
- Each half of the detector shows a 1.5% pixel skew in the ΔY pixel locations.





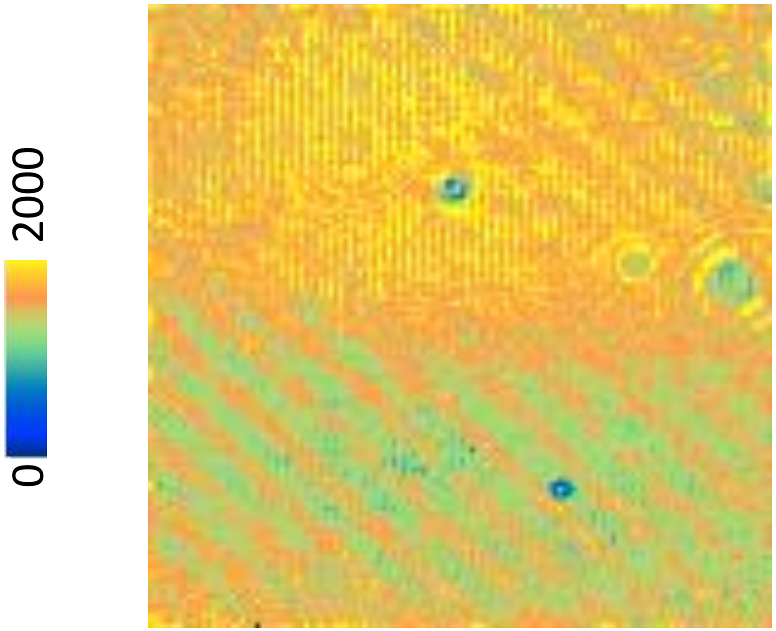
Current Experiment Status

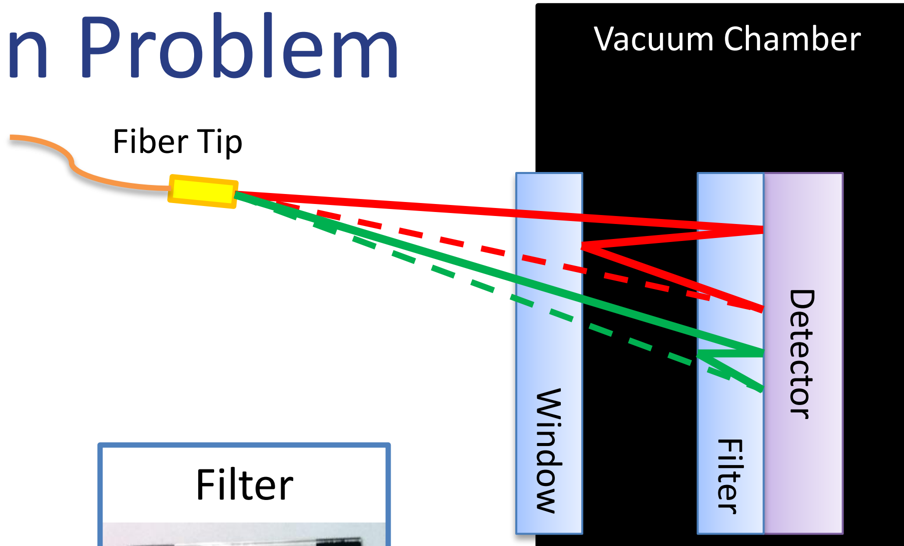
- Testbed designed and built
- Detector
  - Noise levels measured and match expectations
  - Gain matches expected values
  - Detector nonlinearity observed and calibrated out. Laser intensity adjusted to try to stay within most linear region.
- Fringe Quality
  - Camera internal reflections causing problems
- Data Collection
  - Several preliminary datasets have been collected. Results show need to mitigate internal reflections.
- Data Processing
  - Data management software completed for managing 10,000's of images
  - Data processing performed in custom C++/CUDA software

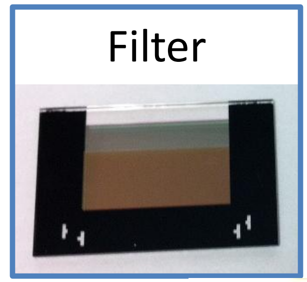
Current Challenges

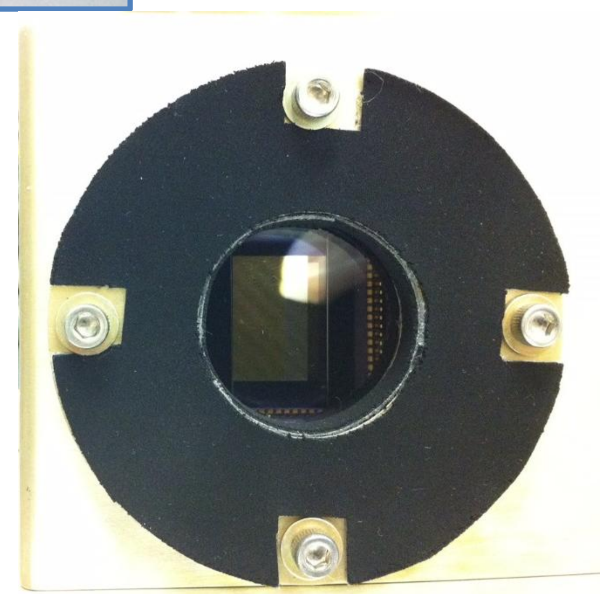
- Camera saturates before entire frame can be read when dark. Currently can only characterize 128x128 region of the chip at a time.
- Spurious Fringes - Reflections between the detector chip and other surfaces are causing artifacts in the images.
  - Camera is inside of a vacuum sealed container which has a glass window.
  - Borrowed camera has a filter glued on the detector.
  - Remedies:
    - Post-process data to remove artifacts
    - Modulate light such that artifacts move around and are averaged out
    - Place entire experiment in vacuum chamber (not just detector)

Internal Reflection Problem









- Fringes caused by the window, can be removed by tuning the laser a few Ghz.
- Fringes from the filter that’s glued to the detector are harder to remove.
- But we can argue that this is not a systematic error but the signal. (the fringe from the filter changes the effective QE(x,y) within a pixel that produces photometric and astrometric errors. These errors are removed/reduced when the det/filt data are reduced using the metrology data.

Summary

- Subpixel characterization is needed for WFIRST to increase accuracy of astrometry measurements, and aid in removing detector errors in ellipticity measurements.
- Pixel position and higher order terms of intrapixel QE(x,y) can be measured by projecting laser fringes on the detector.
- Method has been demonstrated on CCD cameras with centroid error $< 10^{-4}$ pixel/image ellipticity err $< 10^{-3}$/image
- Characterization of a borrowed H2RG detector is underway

- But the current H2RG has a filter glued to the front of the chip. In the not too distant future, it would be more useful to the WFIRST project for us to test a H4RG detector.

Since WFIRST Meeting

- The borrowed detector was been cleaned up,
  - Almost all of the dust that caused the black dots with diffraction rings have been removed.
  - A new cold filter is in place to block thermal radiation from the room to the detector, significantly reducing the background to the detector
- Believe we can now measure pixel positions to close to 1e-3 pixels.
  - When the fringe spacing is >> 1 pixel, the fringe phase measures the pixel position. Different spacing fringes measure the pixel position with a different scale factor, but once corrected for that scale factor, the two measurements should give the same pixel offsets.
  - We're in the process of validating our measurements.
  - The next stage is put airy spots on the detector and measure centroiding precision as well as ellipticity measurements. (with and without applying pixel position offsets.
  - The pixel position offset is very close to a measure of the QE gradient within a pixel.
  - After that we'll start to apply fringes whose fringe spacing is close to, equal to and smaller than a pixel width. And characterize higher order QE variations within a pixel.
  - One expects some QE nonuniformity within a pixel, one questions is how repeatable is that between pixels.